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# TEMPERATURE CHANGES IN THE NORTH-WESTERN ITALIAN ALPS FROM 1961 TO 2010

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**Abstract:** The aim of this study was to identify any possible temperature changes within the last 50 years in the North-Western Italian Alps by examining data from 16 high-altitude weather stations in the period 1961-2010. The daily temperature time series were collected, digitized, subjected to an historical research to individuate discontinuities and retrieve metadata. We also carried out the data quality control and the homogenization which allowed the climatic indices trend detection. The analysis of the temperature values showed an increase in temperature, particularly at high altitudes sites. In fact, the stations located above 1600 m asl revealed a rise in temperatures and a decrease in the number of cold periods. For the maximum temperatures have been observed greater increases in spring and winter, for minimum temperatures in the summer. These trends confirm that climate change is occurring in an environment particularly sensitive to temperature changes, especially during the season of snow accumulation and vegetative growth. These results may be important for policy makers to define the best adaptation strategies in order to protect one of the most sensitive environments such as mountains.

**Key words:** temperatures, climate change, climate indices, North-Western Italian Alps.

## 1. Introduction

Global recent climate changes have been investigated and described in many studies (Alexander et al. 2006; Aguilar et al. 2005; Barriopedro et al. 2006; Bradley et al. 1987; Dos Santos et al. 2010; Karl et al. 1993; Liu and Chen 2000).

The global average warming in the twentieth century has been estimated to be at about 0.6 °C (Jones and Moberg 2003). Luterbacher et al. (2004) analyzed the trends and extremes of European temperature, with a dataset from the 1500 to 2000, and found that in the 20th century was the warmest since 1500 with a strong warming trend of 0.08°C ± 0.03°C per decade and that the nine warmest European years on record have occurred since 1989 ( $\Delta T = +1.3^\circ\text{C}$ ). In Italy, an increase of approximately 1 °C has been measured over the last 50 years of the twentieth century (Brunetti et al. 2000a; Toreti and Desiato 2008, 2007).

As reported by Lionello et al. (2012), the temperature in the Mediterranean are characterized by high spatial complexity and a pronounced seasonal cycle, and they are influenced by large-scale atmospheric circulation land-sea interactions, and local processes (Terzago et al. 2013; Trigo et al. 2006; Xoplaki et al. 2003). In the past six decades, in the Mediterranean areas, an overall warming trend has been reported (Brunet et al. 2007; Brunetti et al. 2009; Kafle and Bruins 2009; Toreti et al. 2010). The recent upward tendency, started in the western Mediterranean followed by increases in the eastern part (Miranda and Tomé 2009; Tayanç et al. 2009), shows a trend particularly pronounced in summer, while several locations do not show a significant trend in winter (El Kenawy et al. 2009; Toreti et al. 2010), although on a centennial timescale, trends are highly significant in all seasons (Brunetti et al. 2009).

The whole Mediterranean region has been considered sensitive to actual (Giorgi 2006) and future climate changes, as established by many studies through the use of climate model simulations (Giorgi and Lionello 2008; Lionello et al. 2006a,b; Ulbrich et al. 2006). In this context, for its geomorphological characteristics, the Alpine region is one of the most sensitive environments to climate change (Knoche 2011). Since 1996, the IPCC has underlined the need to understand and predict the effects of climate change in mountainous regions through monitoring, experimental studies and modelling. A change in the alpine climate regimes can in fact, influence winter precipitation (IPCC 2007; Valt et al. 2006), and the persistence of the snow cover, can lead to impacts of considerable magnitude (Ronchi and Loglisci 2008) on river systems and on the socio-economic structures (Fazzini et al. 2004) of the populations that live in the mountains and valleys (Beniston et al. 1997; Hill Clavis 2013). The positive trend observed for winter temperatures is closely linked to the reduced snow cover that has been observed in recent years in the Alps (Jacobson et al. 2004; Rebetez and Reinhard 2008; Serquet et al. 2013).

In terms of climate research, the European Alps constitute a region of high potential (Auer et al. 2007; Barontini et al. 2009; Böhm et al. 2001; Brunetti et al. 2009; Casty et al. 2005; Durand et al. 2009; Matulla et al. 2005; Van der Schrier et al. 2007). The Alpine region is in fact, a transition zone between three climatic zones (the Atlantic Ocean, the Mediterranean Sea and the European mainland; see for instance: Bartolini et al. 2009; Jungo and Beniston 2001) to which the effects of altitude have been added (Auer et al. 2005).

Among the numerous studies on the Swiss Alps, Beniston and Rebetez (1996) and Beniston et al. (1997) showed that there is a correlation between the variation in temperature and altitude. Diaz and Bradley (1997) analyze elevational differences in long-term temperature trends, using high-elevation station records from various locations over the world, and found that the warming of the surface temperature is strongest for high altitude site. In more recent studies, it has been observed that the greatest temperature changes have been recorded in the cold seasons, when the anomalies of the daily maximum can reach 20 °C or more (eg December 17<sup>th</sup> 2005, Fratianni et al. 2009), compared to the increment of 10 °C observed for the summer heat waves (Beniston 2005).

The data measured at global level do not allow us to have a clear picture of the ongoing work at a local scale. Jungo and Beniston (2001) through a study on the Swiss Alps were able to identify an increase in temperatures of up to 2 °C between 1901 and 2000. However, there are many gaps in Italy, compared to other neighboring states, although some national studies have been conducted (Brunetti et al. 2006; Brunetti et al. 2001a; Brunetti et al. 2000a, b; Cacciamani et al. 2001; Corti et al. 2009; Maugeri and Nanni 1998; Toreti and Desiato 2008, 2007).

The Alpine region has been the subject of many studies, but more broad-spectrum studies have been conducted over the eastern Alps (Bocchiola and Diolaiuti 2010; Brugnara et al. 2012; Brunetti et al. 2001b; Di Piazza and Eccel 2012, Fazzini and Gaddo 2003) than over the western Alps (Ciccarelli et al. 2008; Mercalli et al. 2008). The recent studies in this area are mostly of a very localized nature, such as Acquaotta and Fratianni (2013a), which deals with an analysis of rainfall time series in Piedmont, or that of ARPA Piemonte (2012), on the climatological atlas of Verbano CusioOssola and, or of Fratianni and Motta (2002) that consider the Susa valley, or Nigrelli and Collimedaglia (2012) pertaining to the Alpe Devero and Domodossola meteorological stations, or still those of Biancotti et al. (1998), Valt et al. (2008 and 2006) and Terzago et al. (2012 and 2010) and Acquaotta et al. (2013b) which are focused on the analysis of snow depth and snow precipitation on Italian Alps.

Considering other indicators of global climate change, Harris et al. (2003) on a study of permafrost explain that *"reacts sensitively to changes in atmospheric temperature"* and still Harris et al. (2003) analyzing further studies highlight (Dramis et al. 1995; Haeberli 1992; Haeberli et al. 1997; Haeberli and Beniston 1998; Harris et al. 2001a,b) *"it is predicted that degradation will lead to an increased slope instability in lower latitude mountains"*.

Carturan et al. (2013) analyzing the changes in area, length and volume of the glaciers in the Ortles-Cevedale group (centre-eastern Italian Alps) from the 1980s to the 2000s, found links between the behaviour of glaciers (retreat) and the meteorological data series recorded at 2605 m by the Careser dam weather station. In that station were recorded strong positive trends for both annual (0.5 °C per decade) and summer (0.6 °C per decade) temperatures. Huss (2012) evaluating the glacier mass balance in the European Alps over the 20<sup>th</sup> century identifies a strongly negative mass balances for the 1940s and the last two decades when the average annual balance approached -1 m w.e. a<sup>-1</sup>. The mean area-averaged mass balance in the European Alps is  $-0.31 \pm 0.04$  m w.e. a<sup>-1</sup> for 1900–2011 corresponding to a total ice volume change of  $-96 \pm 13$  km<sup>3</sup>. A previous study of Haeberli (1990) relates the increase of air temperature of 0.5 °C to 1.0 °C occurred in the 20<sup>th</sup> century and correlates it with the mass loss of glaciers in the middle and low latitudes and the decrease the length of the Alpine valley glaciers.

As regards to future models and scenarios Huss (2012) estimated an increase of the average air temperature by 2–5 °C by 2100 (relative to 1961–1990 annual average air temperature using Global Circulation Model), while the annual precipitation totals remain almost constant. His models indicate a general trend to drier conditions and warming greater than the annual average in summer. Future glacier mass balance at the scale of the European Alps is expected to show a negative trend over the next decades for all scenarios. Marzeion et al. (2012) have presented a model, to reconstruct the annual glacier surface mass balance based solely on monthly temperature and precipitation data. The source of data for temperature and precipitation used in that study was the HISTALP dataset (Auer et al. 2007). On the scale of the whole alpine region, the study of

Marzeion et al. (2012) report that the temperature slightly dominates precipitation as the driver of mass balance variability, and identify a positive temperature anomaly during the winter.

In the frame of the study of the influence of the North Atlantic Oscillation (NAO) on mass balance variability of European glaciers, Marzeion and Nesje (2012), according to Reichert et al. (2001), highlight on the western Alps that the winter precipitation and temperature anomalies cause a weak anticorrelation between mass balances and NAO. While in the eastern Alps, a weak positive correlation between NAO and mass balances, in the more central and southern parts of the Alps, the lack of a precipitation signal leads to a weak anti-correlation between mass balances and NAO.

This work will deepen the existing knowledge and give an overview of climate change over the northwestern Alps. The aim of this study is focused on the temperature data analysis over the last five decades through the use of a new daily temperature time series from high-altitude meteorological stations (from 700 m asl to 2400 m asl). This high-quality dataset has a good temporal continuity and was recovered, digitized and then subjected to a strict quality control and homogenization to avoid any non-climatic variations that could affect the analysis. Since the mid 20<sup>th</sup> century, the study area has been monitored by the installation of several weather stations. However these data have yet to be used in a single study. In most cases, the development of the monitoring network, has only enriched the public body data archives. This rich meteorological dataset has been collected over the years contains a set of precious information, which, even today, not only allows one to recognize the climatic variations that have occurred in a zone, but also to cast light on the formation mechanisms of the climate, and to makes future forecasts easier.

## **2. Geography of the North-Western Alps**

The area of North-Western Italian Alps analyzed in this work, develops within the territories of Piedmont region. Interestingly from South to North the Ligurian, Maritime, Cottian, Graian, Pennine and Lepontin Alps. The territory covers approximately 25399 km<sup>2</sup> accounting for about 4.3 million inhabitants. The Alpine region is bordered by Switzerland, France, and the Italian regions of Lombardy, Aosta Valley and Liguria.

The Piedmont region (Figure 1) is made up of three geomorphological areas: mountains (Alps and Apennines), hills (Monferrato and Langhe) and plain.

The mountain area covers about 12000 km<sup>2</sup> and includes the highest mountains in Italy and in Europe: the Monviso (3841 m asl), Rocciamelone (3538 m asl), Punta Ciaramella (3676 m asl) and Argentera (3297 m asl). The plain covers 6450 km<sup>2</sup>, including the area between the foot of the Alps and the hills of Monferrato and Langhe. The hilly area covers 6570 km<sup>2</sup> and it is composed of the hill of Turin, the Langhe and Monferrato.

Two main factors induce the thermal-pluviometric characteristics of Piedmont: the orography, the greater internal factor, and the atmospheric circulation with dry continental air flowing in from Po Valley in the east and relatively moist Mediterranean and Atlantic air coming in with north-western flows.

## **3. Historical time series**

This work has allowed us to recover and analyze long-term daily temperature series (covering approximately the last 8 decades) of 16 high-altitude manual stations. Most of them are located close to reservoirs, made by the National Energy Authority (ENEL), for electricity exploiting. The main advantages of this weather network are: the high-altitude location of the stations; the availability of a complete archive of metadata and no significant changes in the environment surrounding of the stations.

For each meteorological station we recovered the handmade register and digitized all daily data. Since the registers also contain information on changes in the instrumentation and location, a metadata file associated with the station data file was created as well. It contains the location of the station (geographical coordinates and altitude), the nearby basin, the instrumentation and all reported changes.

The weather stations are distributed across the Piedmontese Alps, from the Maritime Alps to the Lepontine Alps, at altitudes between about 700 m and 2400 m, representative of all Alpine sectors, with the exception of the Ligurian Alps (Figure 1).

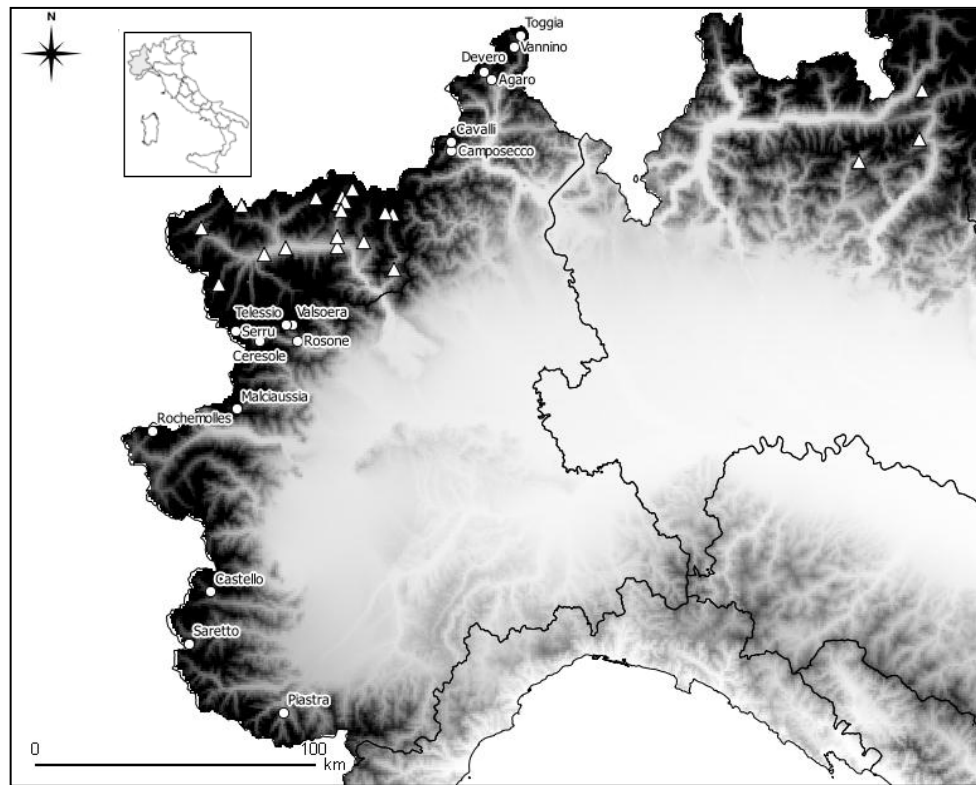


Figure 1. Study area with the meteorological stations (dots) and series used for the homogenization (triangles).

The longest retrieved time series are the ones of Rochemolles, Cavalli and Ceresole with data from 1926, 1930 and 1932, respectively. From 1934 to 1938, four stations began their activity and by 1961 the number of available weather stations reached 15 (Table 1). Thus, the 50-year period of activity from 1961 to 2010 was selected to perform the analyses and identify the peculiarities of the high-altitude stations in Piedmont. However, gaps affect the investigated time series also in the selected time period. The stations with largest number of missing data (4% of the daily records) are Rochemolles and Rosone followed by Devero with 2% of missing days.

The station Piastra was added to cover the Maritime Alps area and increase the number of stations between 700 m and 1000 m asl. Their data record started in 1968, and to remember that this station does not cover the entire period, Piastra will hereafter be identified as Piastra\*.

Table 1. Main characteristics of the meteorological stations.

N.	Weather Stations	ID	Alpine Sector	Activity period	Altitude [m asl]	Coordinates	
						Lon.	Lat.
1	Lago Valsoera	Valsoera	Graian A.	1959-2010	2412	7.3957	45.4868
2	Camposecco	Camposecco	Pennine A.	1951-2010	2316	8.1169	46.0589
3	Lago Serrù	Serrù	Graian A.	1961-2010	2283	7.1356	45.4611
4	Lago Vannino	Vannino	Lepontine A.	1951-2010	2177	8.4019	46.3986
5	Toggia	Toggia	Lepontine A.	1937-2010	2165	8.4300	46.4361
6	Rochemolles	Rochemolles	Cottian A.	1926-2011	1950	6.7672	45.1317
7	Lago Pian Telessio	Telessio	Graian A.	1959-2010	1940	7.3683	45.4844
8	Malciaussia	Malciaussia	Graian A.	1937-2010	1800	7.1494	45.2086
9	Alpe Devero	Devero	Lepontine A.	1951-2010	1634	8.2611	46.3169
10	Agaro	Agaro	Pennine A.	1961-2010	1600	8.3017	46.2917
11	Lago Castello	Castello	Cottian A.	1943-2010	1589	7.0511	44.6139
12	Ceresole reale	Ceresole	Graian A.	1932-2010	1573	7.2456	45.4311
13	Acceglio Saretto	Saretto	Cottian A.	1934-2010	1540	6.9586	44.4444
14	Alpe Cavalli	Cavalli	Pennine A.	1930-2010	1500	8.1167	46.0878
15	Lago Piastra	Piastra*	Maritime A.	1968-2010	960	7.3894	44.2281
16	Rosone	Rosone	Graian A.	1938-2010	701	7.4194	45.4353

## 4. Methodology

The retrieved temperature data underwent quality control in order to check for any possible mistakes in the time series. For example, human errors due to digitization process or the original data registration. The data check was carried out using the software RCLimdex (Zhang and Yang 2004), which allowed us to identify data transcription errors, for example, a maximum temperature less than minimum temperature and also identified outliers in daily maximum and minimum temperature. The outliers are daily values outside a interval, in this work the interval, in agreement with Acquafredda et al. (2009) and Aguilar et al. (2005), is the mean plus or minus 4 times standard deviation of the daily value. All the values out of this range were placed in a separate file, then we have performed another check on the data to define if any value marked was really an outlier. The check was accomplished by comparing the values with the original records, and then the consistency was verified in the range of 5 days before and after the outlier and using neighbouring stations and historical newspaper.

We used the monthly averages only if was available at least the 80% of daily data, equal to a gap of 6 not-consecutive days (Klein Tank et al. 2002; Sneyers 1990) and for the annual averages, at least the 94% of the daily data, equal to a gap of 20 not-consecutive days (Klein Tank and Können 2003).

Conrad and Pollack (1962) before and Peterson et al. (1998) after, explain that we have a homogeneous time series when the variations are due only by variations in climate. Therefore, in order to perform the climatic analysis, the daily temperature data were subject to a homogenization process. To homogenize the variables we have employed the SPLIDHOM method (Mestre et al. 2011; Venema et al. 2012). The test is fully based on non-parametric regression, and relies on cubic smoothing spline. The use of a smoothing parameter set by means of cross-validation allows avoiding over fitting during the estimation process. The SPLIDHOM method, to be applied with good results, recommends a correlation, between the candidate series and the reference series, possibly equal or greater than 0.8. The dataset of historical series was improved with 20 reference series from Aosta Valley and Lombardy regions, with comparable topographical features. However, for the correction of the series are been used only the metadata identified by historical research.

The trends, of meteorological variables, TX and TN, and climate indices have been calculated for the monthly, seasonal and annual values. The trends were computed using the Theil-Sen Approach (TSA) (Sen, 1968; Zhang et al. 2000; Toreti and Desiato 2008). The trend is removed from the series if it is significant and the autocorrelation is computed. This process is continued until the differences in the estimates of the slope and the AR(1) (Autoregressive model) in two consecutive iterations are smaller than 1 percent. The Mann-Kendall test for trend is then run on the resulting time series to compute the level of significance. TSA is preferred to the linear least square that is more vulnerable to gross error of data and has a confidential interval more sensitive to the non normality of the distributions.

Six temperature indices (Table 2) are selected from the list of 27 core climate extreme indices defined by the Expert Team (ET) and its predecessor, the CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) and recommended by the World Meteorological Organization – Commission for Climatology (WMO-CCL). For percentile indices (e.g., the number of days exceeding the 90th percentile of minimum temperature or maximum temperature) the methodology uses bootstrapping for calculating the base period values so there is no discontinuity in the indices time series at the beginning or end of the base period (Zhang et al. 2005). The selected base period for the percentile indices was 1971–2000.

*Table 2: Climate indices*

ID	Indicator name	Definitions	UNITS
<b>TX</b>	Tmax	Mean maximum value of daily maximum temp	°C
<b>TN</b>	Tmin	Mean minimum value of daily minimum temp	°C
<b>TN10p</b>	Cool nights	Percentage of days when TN<10th percentile	% Days
<b>TX10p</b>	Cool days	Percentage of days when TX<10th percentile	% Days
<b>TN90p</b>	Warm nights	Percentage of days when TN>90th percentile	% Days
<b>TX90p</b>	Warm days	Percentage of days when TX>90th percentile	% Days
<b>WSDI</b>	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	Days
<b>CSDI</b>	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN<10th percentile	Days

The Standardized Anomaly Index (SAI) has been calculated for maximum and minimum temperature of all the stations, using as reference period the 1971-2000. Finally, the SAI results were divided for the altitude of the stations in two groups, upper or equal to 1600 m asl and below the 1600 m asl.

## 5. Results

### 5.1 Homogenization

The database, used to homogenize the maximum and minimum temperature series for this study (Table 3), includes 17 series recorded from 1928 of Aosta Valley and 3 from 1951 of Lombardy (Figure 1). The historical research on the Piedmont stations has highlighted averagely 2 breaks (Figure 2 left). The breaks highlighted in the early of 21<sup>th</sup> century, in most cases are due for a change of location or instruments of the weather stations. In this period, across the 2002 and the beginning of 2003, the manual stations were replaced by automatic stations for a reorganization of the meteorological network. The second most important breaks shown by the historical research are due by a change of instruments, from a maximum and minimum thermometer to a thermograph. In some stations, Ceresole, Rosone, Agaro, Rochemolles and Toggia, were highlighted breaks due to a changes in the time of instrument reading.

For every location we have created a metadata file that shows: the locations of the meteorological station, the basin it belongs to, the latitude, the longitude, the altitude, the instrument type, the change of location or instrument, and the operating periods. In addition, for each meteorological station, cartographical maps with different levels of detail have been drawn, while the photographic documentation completes the information. The cartography, obtained from the Regional Technical Cartography (CTR, scale 1:10,000) and from the map of Italy (scale 1:25,000) of the Military Geographical Institute, Cartographic State Agency, show the relative position of the stations (Figure 2 right) (Acquaotta et al. 2013c).

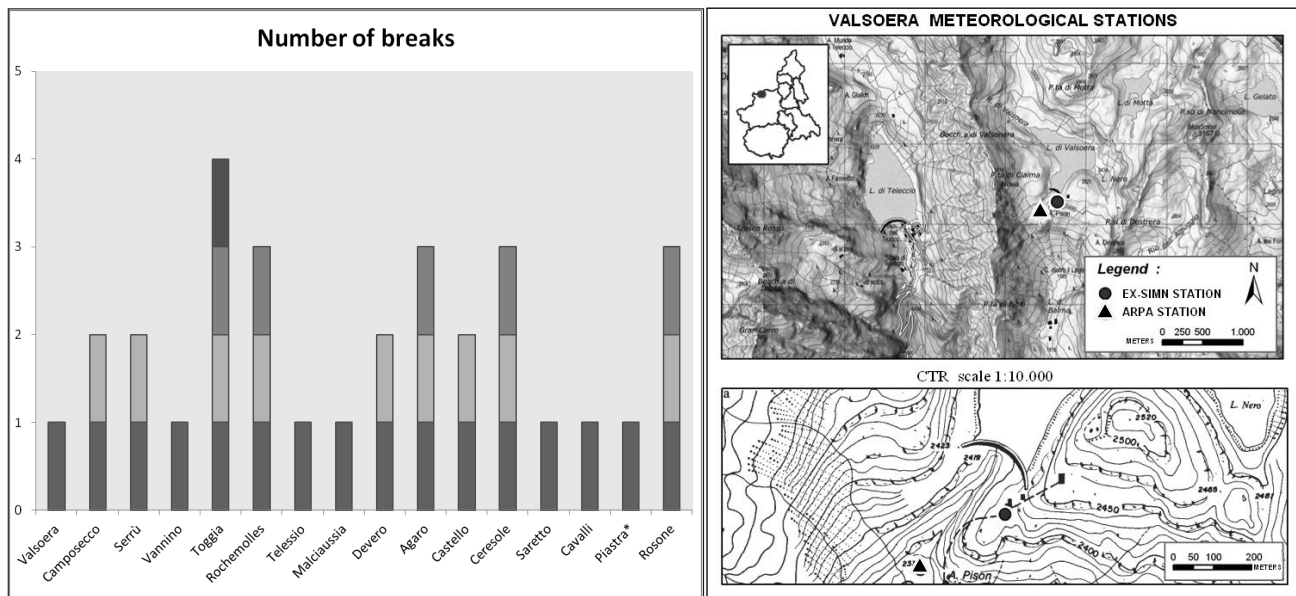


Figure 2. Left panel: number of breaks highlighted in the stations; right panel: cartographic map of a station, example of a relocation from manual station (EX-SIMN station) to automatic station (ARPA station).

For each station and for both the series, maximum and minimum temperature, were selected averagely 3 reference stations with high correlation coefficient and a mean distance of 94 km (Table 3). For the minimum temperature the mean difference of elevation between the candidate series and reference series is equal to 370 m while for the maximum temperature is equal to 345 m (Table 3).

Table 3. Relationship between candidate and reference series for minimum and maximum temperature.

Candidate series	Minimum Temperature				
	Altitude (m)	Mean altitude of reference stations	Mean corr coef	Number of reference stations	Mean distance (km)
Valsoera	2412	1880	0.93	4	94
Camposecco	2316	1766	0.93	4	50
Serrù	2283	2035	0.87	2	106



Vannino	2177	1737	0.90	4	75
Toggia	2165	1176	0.79	3	113
Rochemolles	1950	1612	0.76	5	109
Telessio	1940	1564	0.93	4	61
Malciaussia	1800	1212	0.86	2	102
Devero	1634	1805	0.78	2	47
Agaro	1600	1945	0.94	4	56
Castello	1589	1601	0.79	5	140
Ceresole	1573	1550	0.86	6	74
Saretto	1540	1133	0.77	3	133
Cavalli	1500	1186	0.91	1	52
Piastra*	960	1255	0.87	2	107
Rosone	701	1227	0.85	4	56

Stations	Altitude (m)	Maximum Temperature			Mean distance (km)
		Mean altitude of reference stations	Mean corr coef	Number of reference stations	
Valsoera	2412	2027	0.86	3	110
Camposecco	2316	1833	0.90	2	26
Serrù	2283	2212	0.83	3	144
Vannino	2177	1917	0.89	3	34
Toggia	2165	1575	0.73	2	107
Rochemolles	1950	2291	0.79	2	171
Telessio	1940	1777	0.89	3	71
Malciaussia	1800	1244	0.79	4	121
Devero	1634	2168	0.83	2	16
Agaro	1600	1819	0.89	4	48
Castello	1589	1596	0.74	5	138
Ceresole	1573	1801	0.85	2	69
Saretto	1540	1187	0.70	4	163
Cavalli	1500	1335	0.83	4	57
Piastra*	960	1303	0.75	4	123
Rosone	701	1471	0.79	3	58

Before analysing the homogenized data the difference between the original and homogenized data are discussed. Figure 3 shows the mean annual adjustment curves for maximum and minimum temperature. The large standard deviation range (grey lines) underline again the absolute necessity to homogenize in order to get any reasonable single-station series. Some systematic biases in the adjustment curves are evident. In the early period, from 1961 to 1979, for both the temperature series the average of the difference series reveals a general increasing due to a change of instruments, from the thermometer to the thermograph, by a progressive technological evolution of the meteorological stations. The second step start from 1987 when on the study area a new meteorological network was created, belonging to ARPA Piedmont, to improve the quantity of meteorological data on the region in order to better explain the complexity of the territory for forecasting purposes. These corrections influence the trends of minimum and maximum temperature in the 1961-2010 period. In particular the increase of the temperature recorded in this century is underestimate because in the cool period, 70s years, the correction factor increase the temperature averagely of 0.5°C for minimum temperature and 0.6°C for maximum temperature while in the last period the factor decreases the temperature averagely of -0.1°C for both the variables.

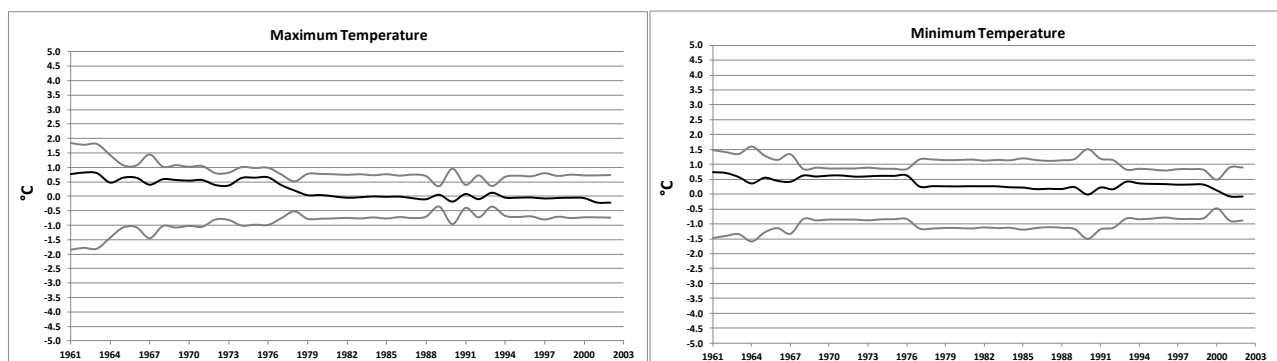


Figure 3. Adjustment curves, homogeneous minus original data, averaged over 16 locations for maximum temperature (left) and minimum temperature (right); black lines mean, grey lines the standard deviation range.

## 5.2 Average monthly temperatures

The stations located at an altitude greater than 2000 m asl measured the higher values of maximum monthly average temperature between 12.3 °C of Toggia and 15.0 °C of Serrù both in July, while the lowest, in winter, are between -0.7 °C of Camposecco and -3.5 °C of Toggia.

The lowest values are between -11.9 °C of Toggia and -9.1 °C of Camposecco and Serrù in January and February. The highest values, instead, are recorded in August, with values between 5.0 °C of Vannino and 6.4 °C of Camposecco.

The stations with altitude between 2000 m asl and 1000 m asl measure higher values of the maximum monthly average temperature between 15.8 °C of Telessio and 21.9 °C of Saretto in July. The minimum values, between 1.1 °C of Telessio and 5.9 °C of Saretto in January and December.

The highest values of minimum monthly average temperature between 8.1 °C of Rochemolles to 11.9 °C of Castello are in July and August. In January and February the temperatures vary between -5.3 °C of Cavalli and -10 °C of Devero. Generally in these stations the monthly average minimum temperature never exceeds 0 °C from November to March. In some locations minimum temperatures below 0 °C are measured occasionally in the month of April. In these months the temperatures vary between -2.5 °C of Devero and -0.2 °C of Cavalli (other locations with these values are Rochemolles, Telessio, Malciaussia, Agaro and Ceresole).

The stations located at an altitude less than 1000 m asl, estimate a maximum monthly average temperature between 27.1 °C in August and 2.4 °C in January recorded at the station of Rosone. For minimum temperature, between 13.4 °C of Piastra\* in August and -4.9 °C of Rosone in January. Values below 0 °C are measured from December to February and, only for the Rosone station, also in March.

For the maximum temperature the difference between the lower and higher values is more pronounced at low altitudes ( $\Delta t$  between 20.6 °C and 24.7 °C) than at higher elevations ( $\Delta t$  between 13.1 °C and 16.8 °C). Instead for the minimum temperature the difference between the lower and higher values is almost similar at all the altitudes ( $\Delta t$  between 14.7 °C and 17.8 °C).

## 5.3 Trends and indices

We have estimated the trends of maximum and minimum temperature on the Piedmont Alps in the last 50 years, from 1961 to 2010. The analysis highlights a significant warming tendency in most of the locations. Only in Castello station (1589 m asl) a not-significant decreasing tendency have been estimated (Tables 4). The more complex behaviour of Castello station is related to the topographic characteristics of the measurement area. This is a bottom valley station, oriented NW-SE along the direction of the prevailing winds, where the cold air tends to stagnate, especially in the evening.

Table 4. Annual estimated trends, from 1961 to 2010, for maximum (TX) and minimum (TN) temperature and the related climate indices (TX90P, TX10P, WSDI, TN90P, TN10P and CSDI). For each trend, we report slope and the statistical significance (starred: \* 90%, \*\* 95% and \*\*\* 99%), the symbol // means no trend.

Weather Stations	Elevation (m)	TX	TX90P	TX10P	WSDI	TN	TN90P	TN10P	CSDI
Valsoera	2412	0.067***	0.410***	-0.135	//	0.077***	0.397***	-0.170**	//
Camposecco	2316	-0.003	-0.041	-0.055	//	0.069***	0.215***	-0.355***	-0.298***
Serrù	2283	-0.002	-0.044	0.020	//	0.052*	0.301***	-0.135	//
Vannino	2177	0.036***	0.105**	-0.151***	//	0.069***	0.403***	-0.233***	-0.181***
Toggia	2165	0.038***	0.214***	-0.216***	//	0.024***	0.102*	-0.122**	-0.011
Rochemolles	1950	0.072***	0.328***	-0.162***	0.018	0.018***	0.111**	-0.155**	//
Telessio	1940	0.021	0.283***	0.050	0.018	0.034**	0.200**	-0.103	//
Malciaussia	1800	0.021	0.089	-0.079**	//	0.067***	0.348***	-0.193***	//
Devero	1634	0.005	0.188*	0.132***	0.007	0.027	0.184*	0.021	//
Agaro	1600	0.020	0.107*	-0.033	//	0.016	0.125*	-0.084	-0.010
Castello	1589	-0.006	-0.050	0.002	//	-0.039***	-0.213***	0.191***	0.101**
Ceresole	1573	0.013	0.23**	0.094	0.086	0.007	0.377*	0.071	//
Saretto	1540	0.033***	0.082	-0.171***	//	0.022**	0.099**	-0.162***	-0.030
Cavalli	1500	0.035***	0.178***	-0.051	//	0.025***	0.147***	-0.090	//
Piastra*	960	0.028***	-0.045	-0.022	//	//	0.121*	-0.160***	//
Rosone	701	-0.059***	-0.169***	0.184***	-0.083*	0.016*	0.118	-0.035	//

Table 5. Annual estimated trends, from 1961 to 2010, for maximum (TX) and minimum (TN) temperature.

Series	Trend (°C/year)	$\Delta T$ over the time period (°C)
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TX	0.02***	0.75
TX $\geq$ 2000 m asl	0.02***	1.24
2000 < TX $\leq$ 1600 m asl	0.03***	1.60
TX < 1600 m asl	-0.01	-0.50
TN	0.04***	1.95
TN $\geq$ 2000 m asl	0.06***	2.84
2000 < TN $\leq$ 1600 m asl	0.03***	1.72
TN < 1600 m asl	0.02***	1.10

Rochemolles (1950 m asl) and Valsoera (2400 m asl) stations record the highest trend, respectively 0.072 °C/year and 0.067 °C/year of mean maximum temperature, Toggia (2165 m asl) and Vannino (2177 m asl) stations follow with, respectively, 0.038 °C/year and 0.036 °C/year. The increasing of maximum temperature was recorded in all the seasons, in the stations located at altitudes higher than 2000 m asl and lower than 1600 m, the maximum contribution is in spring (March). The stations located between 2000 m asl and 1600 m asl record the maximum trend in winter (January).

The increase of maximum temperature is also highlighted by the climate indices TX90P and TX10P. The warm days index (TX90P) designed to detect the days with extreme maximum temperatures, show increasing and statistically significant trends. The maximum slope (0.41 % day/year) is calculated in Valsoera followed by Rochemolles with 0.33 % day/year. Only in few locations, Camposecco, Serrù, Castello and Piastra\*, the trends are decreasing but not statistically significant, while in Rosone the trend is decreasing and statistically significant (-0.17 % day/year). The warm spell index (WSDI) shows a slight increasing only for the stations with elevation under 2000 m asl. The maxima of WSDI occurred in 1964 and 2003, while the minimum values in the 1973, 1980, 1984, 1992 and 1997. In some of the stations the cold days index (TX10P) shows a decreasing trend statistically significant. The statistically significant decreasing was calculated in Toggia at the elevation of 2165 m asl (Table 4).

For the mean minimum temperature the trends are increasing and statistically significant in most locations analyzed. The highest slopes are calculated in the stations with elevation greater than 1600 m asl. Valsoera (2412 m asl) shows the maximum value (0.077 °C/year) followed by Camposecco (2316 m asl) and Vannino (2177 m asl) with 0.069 °C/year, and Malciaussia (1800 m asl) with 0.067 °C/year. The increase of minimum temperature was calculated in all seasons but the higher values were recorded in summer in particular in June, while for the locations situated below 1600 m asl in spring in the month of May (Table 4). Also for the warm nights, TN90P, we have calculated increasing and statically significant trends exception for Castello. The higher slopes were estimated always in the stations with elevations upper 1600 m asl. The maximum trend (0.4% day/year) was calculated in Vannino (2177 m asl) and Valsoera (2412 m asl) followed by Ceresole (1573 m asl) with 0.38 % day/year. For the high elevation stations (upper 2000 m asl), the maximum values of warm nights were calculated in 2003, while in the other stations after 2003 in particular in 2007. For the cold waves (CSDI) and cold nights (TN10P) the trends are decreasing and statistically significant above the 2000 m asl. While, for the TN10P the greater decreases were calculated in the stations with elevations upper 1600 m asl. For both the indices, the maximum values were estimated in Camposecco (2316 m asl) (Table 4).

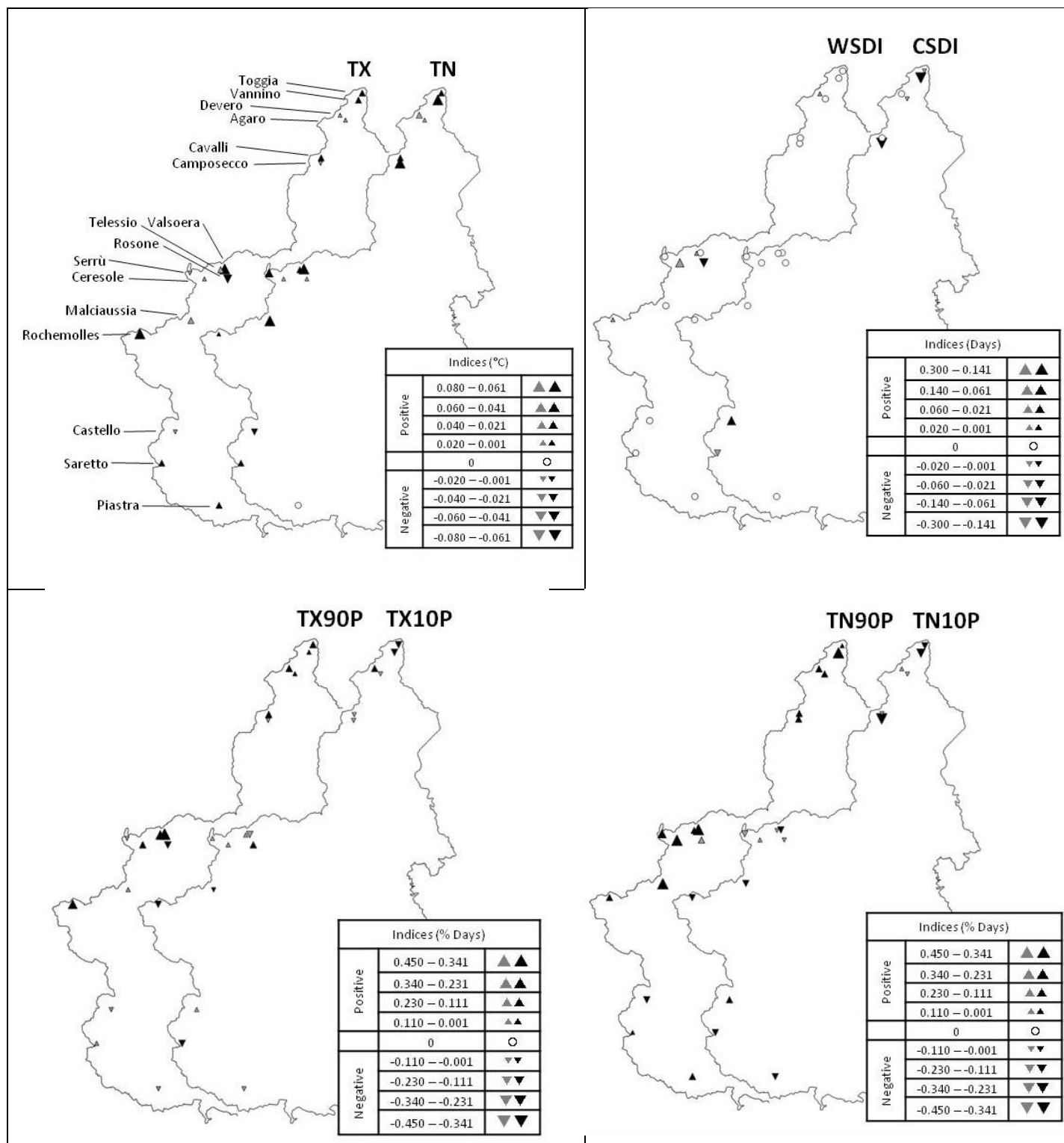


Figure 4: Spatial distribution of the temperature trend. The symbols (▲) for positive and (▼) negative trends, statistically significant at 90%, while the symbols (△) the positive and (▽) the negative trends statistically non significant.

The spatial distribution trends of the climatic indices in Table 4 are shown in Figure 4. The different alpine sectors do not show common climate variations. The data show increasing trends in all the sectors of the Alps, but the slopes of the regression lines are different each other.

Homogeneous variations were identified to the different elevations as it emerged from the analysis of trends. The trend estimates allowed to identified 3 ranges of elevations. From the stations with elevations upper 2000 m asl we have calculated a greater increasing of minimum temperature compared the maximum temperature. The estimated trend for the minimum temperature (statistical significant) is 0.06 °C/year with

an increase of 2.84°C in the analyzed period. Between 1600 m and 2000 m asl the maximum and minimum temperatures highlight the same (statistically significant) increase with a trend of 0.03°C/year, respectively equivalent to an increase of 1.6°C and 1.72°C for the entire period. Below the 1600 m asl, the trends of maximum and minimum temperature have different trends, respectively, a non-significative negative trend of -0.01°C/year and a positive statistically significative trend of 0.02 °C/year (Table 5).

Upper or equal to 1600 m the greater increase of minimum temperature was recorded in summer, while in the areas located at an altitude below 1600 m maximum growth is measured in the spring. The maximum temperature highlights similar trends in the three altitude ranges. Upper 2000 m asl the maximum increase was recorded in spring, between 2000 m and 1600 m asl in winter and below 1600 m asl in spring.

The asymmetry observed between maximum and minimum temperature trends in North-West of Alps is consistent with similar observations deduced by other study on Alps (Beniston et al. 1997 and Beniston 2005), on sub-continental scale (Luterbacher et al. 2004) and on the global scale (IPCC 2013) have shown that over much of the continental land mass, minimum temperature have risen faster than the maximum temperature.

In the same study area (NW Italian Alps), Terzago et al. (2013) and Acquaotta et al. (2013b) have found a decrease of snow depth in all the stations over seasonal (November–May) time scale in the period 1951–2010. The main valued contribution for to this negative trend comes from spring when the snow depth decrease is comparable to the one registered over the complete season. Furthermore, the authors have identified that around 1500 m asl, the strength of the snow depth decrease. Besides the strongest spring snow depth reduction, the Northern stations suffer also a significant snow depth decrease during winter months, so, North Piedmontese Alps result the most sensitive to climate change. In a future work may be related to the results obtained in these papers, increasing data with the continuous collection of long time series of other regions, in order to better understand the effects of climate change over the North-Western Italian Alps.

#### 5.4 Standardized Anomaly Index (SAI)

The Standardized Anomaly Index (SAI) has been calculated to evaluate the trend of the maximum and minimum temperatures over the last 50 years (1961-2010), in the Piedmontese Alps. The SAI provides an immediate idea of the degree of anomaly of the behaviour of the temperature recorded in a given year compared to the behaviour of the same variable in a 30-year reference period, here 1971-2000.

The SAI series of maximum and minimum temperatures (Figure 5) have two very similar trends. For both the variables the trends are positive and statistical significant. For the maximum temperature the trend can range from 0.08/10 years to 0.31/10 years while for the minimum temperature from 0.12/10 years to 0.36/10 years. The progressive Mann-Kendall test applied to two SAI series shows a positive trend without changes of slopes. The u and u' time series in the diagrams move parallel to each, which it has not highlight variation on the slope of the trends.

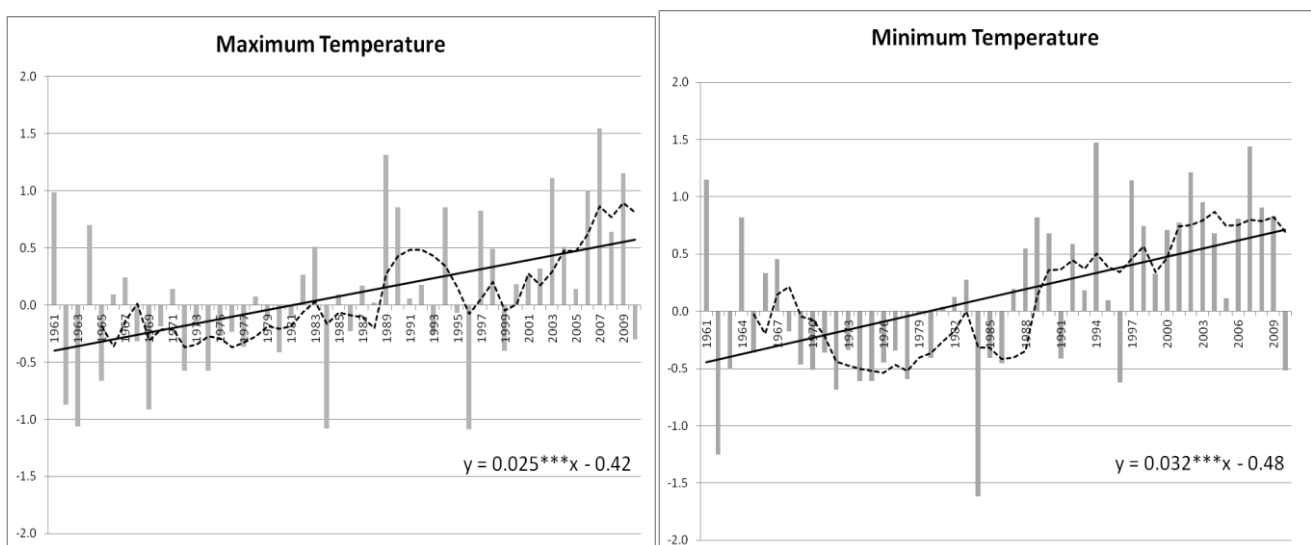


Figure 5: Left, SAI of the maximum temperature from 1961 to 2010; right, SAI of the minimum temperature from 1961 to 2010. The black line

shows the linear trend, the dotted line shows the moving average on 5 years. For each trend, we report slope and the statistical significance (starred: \* 90%, \*\* 95% and \*\*\* 99%).

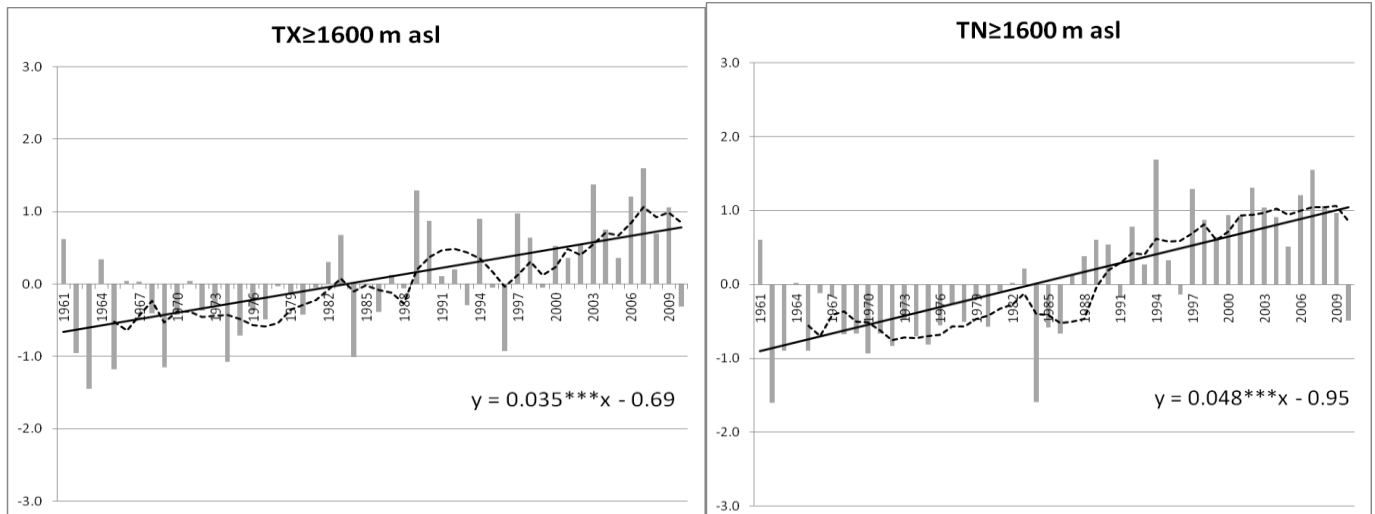
In the first 26 years, from 1961 to 1986, the SAI series shows values lower than average except in a few years. For both maximum and minimum temperatures, the positive values are calculated only in nine years during the 60s and 80s (Figure 5).

Over the next 24 years, from 1987 to 2010, the SAI series show values higher than average in most years, indicating a progressive increase in temperatures. Minimum temperatures below zero values are calculated only in 3 years, 1991, 1996 and 2010, while for the maximum temperatures in 5 years, 1993, 1995, 1996, 1999 and 2010.

The SAI was calculated also on two altitude ranges, elevations upper or equal 1600 m asl and elevations below 1600 m asl (Figure 6). As the SAI calculated on all series the trends for maximum and minimum temperature show a positive slopes and the progressive Mann-Kendall test do not highlight a changes of behaviour. The maximum slope is calculated for minimum temperature ( $0.28 \div 0.51^\circ\text{C}/10\text{years}$ ) following by maximum temperature with  $0.19 \div 0.41^\circ\text{C}/10$  years. For the minimum temperature a positive values of SAI were detected from 1987 while for the maximum temperature from 1997 (Figure 6).

In the zones with altitude below 1600 m the SAI for the maximum temperature does not show long period with positive or negative values. Positive values were calculated at the end of the 60s, 80s and in the 2000s, while negative values in the 70s, early 80s and at the end of the 90s. This behaviour does not allow to calculate any trend. The u and u' time series calculated by the progressive Mann-Kendall test indicate that there is not a meaningful trend and/or a sudden change (jump) in the time series except two period, from 1980 to 1990 and from 2000 to 2010, with a positive slope.

For the minimum temperature we can identify periods with positive SAI, from 1961 to 1969 and from 1987 to 2009, or negative SAI, from 1970 to 1986 (Figure 6). On entire period, from 1961 to 2010, there is not a trend but the progressive Mann-Kendall identifies two period with different behaviour. From 1961 to 1975 a negative trend and from 1976 to 2010 a positive trend. The negative trend,  $-0.003^\circ\text{C}/\text{year}$ , is not statistical significant while the positive trend,  $0.02^\circ\text{C}/\text{year}$ , is statistical significant.



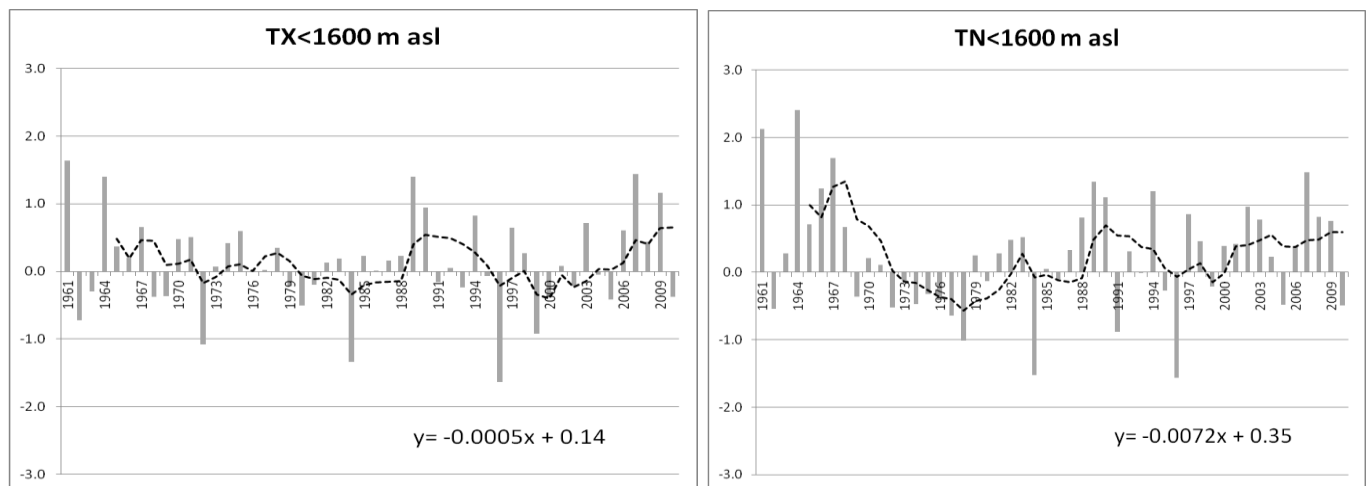


Figure 6: SAI for maximum (TX) and minimum (TN) temperature at altitude greater or equal to 1600 m (upper) asl and below 1600 m asl (lower). The black line shows the linear trend, the dotted line shows the moving average on 5 years. For each trend, we report slope and the statistical significance (starred: \* 90%, \*\* 95% and \*\*\* 99%).

## 6. Conclusions

In the present study, the temperature data from 16 stations in the North-Western Italian Alps have been analyzed using data between 1961 and 2010. The stations are located between 700 m–2400 m asl, and have a manual observation data system. The data were therefore digitized, subjected to a quality control and finally homogenized. The climatic and trend analysis have shown different trends in temperature from station to station, according to the detection altitudes. A positive trend can be observed for the temperature at which an increase in altitude generally corresponds. The stations located above 1600 m asl, in particular, show a rise in temperatures and a decrease in cold periods. The higher trends for these stations were calculated on the minimum temperature, but for both variables, that is, the maximum and minimum temperatures, while the maximum trends were only estimated in the locations at elevations above 2000 m asl. The maximum temperature increase was 0.072 °C/year in Rochemolles (1950 m asl), while the minimum temperature was 0.069 °C/year in Camposecco (2316 m asl). That increase at high elevations, although of different entities due to the different location of the analysis areas, are in agreement with the studies carried out on Alpine permafrost (Haeberli and Beniston 1998; Harris et al. 2001a,b and 2003) and glaciers (Carturan et al. 2013; Haeberli 1990; Huss 2012).

Another interesting fact has emerged from the analysis of the seasonal temperatures. It can be observed that, at the high-altitude stations, the seasons that recorded the greatest changes are different for the minimum and maximum temperatures. The greatest changes for the maximum temperatures were recorded in March and January, while the greatest changes for the minimum temperatures were recorded in June. The maximum temperature analysis highlights an increasing trend in winter between 2000 m and 1600 m asl. This increase at the mid altitudes could adversely affect on the tourist exploitation of the Alpine region. The rising of temperatures will be accompanied by snow losses for winter tourism and skiing season causing impacts on the socio-economic structures (Fazzini et al. 2004) of the populations that live in the mountains and valleys (Beniston et al. 1997).

Moreover, Terzagio et al. (2013) outlines a significant decrease of snow depth in all the Piedmont stations over seasonal (November–May) time scale in the period 1951–2010. The main contribution to this negative trend comes from spring when the snow-depth decrease is comparable to the one registered over the complete season. Besides, the strong links between NAO and snow depth in all the measurement sites and the weaker relation with fresh snow precipitation suggest that NAO mainly controls snow depth via temperature, which affects the snow melt and the vegetative growth season.

The analysis of the climate indices has also made it possible to highlight how the temperatures increased. An increase in the extreme temperature has been measured in all stations. The warm days (TX90P) and warm nights (TN90P) show increasing trends, while the cold days (TX10P) and cold nights (TN10P) indicate decreasing trends. Again for these indices, the highest values were estimated in the stations above 1600 m asl.

In order to evaluate the general variations in the temperature, the Standardized Anomaly Index (SAI) has been calculated. The SAI series of the maximum and minimum temperatures highlights two very similar trends. The index is negative for both variables from 1961 to 1986 and positive from 1987 to 2010.

Again the higher values for this index in the latter period were calculated for the minimum temperature. The SAI trend identified over the two elevation ranges highlights that the increase in temperature is more pronounced in the higher stations at elevations above 1600 m asl. A constant increase has been calculated from 1987 onwards, especially for the minimum temperatures, while the maximum temperatures have shown a more steady increase since 1997. The zones below 1600 m asl have shown a less constant trend. The maximum and minimum temperatures show alternating periods of growth and decline. However, in the last period, from the end of 90s, a steady growth has been calculated for both variables.

Although further studies are needed, considering a greater number of data from weather stations, this paper has shown that the recorded increase in temperature is greater in the high elevation sites than in the foothill zones. High elevations seem to amplify the climatic signal.

The gathered information shows the importance of meteorological data collection networks at high altitudes, first in order to characterize the climatological features and then to understand the climate change, but also as a means of providing useful information for the climate modelling community. In this context, an accurate analysis of climatic changes in the mountains is necessary since the results could be extremely important for policy makers in order to define the best adaptation strategies necessary to protect one of the most sensitive environments, that is, the mountains.

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